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NACA

RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF AIR-COOLED TURBINE BLADES IN TURBOJET ENGINE

XIII - ENDURANCE EVALUATION OF SEVERAL PROTECTIVE COATINGS APPLIED TO TURBINE BLADES OF NONSTRATEGIC STEELS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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SUMMARY

Durabilities of several protective coatings applied to air-cooled gas turbine rotor blades of nonstrategic steels (SAE 4130 and Timken 17-22A(S)) were investigated in modified turbojet engines. Four types of coatings, ceramic, nickel, Nicrobraz, and aluminized (diffused aluminum), were applied to a total of 20 blades. Coatings were endurance-tested for extended periods at the maximum rated speed and turbine inlet temperature of the engine used. Continuous operation at these conditions is limited to half-hour periods in service.

Ceramic, aluminized, Nicrobraz, and a combination of nickel and Nicrobraz coatings each provided satisfactory corrosion and erosion protection to at least one blade for 100 hours with ratios of cooling-air to combustion-gas flow between 0.030 and 0.048. Aluminizing gave excellent protection, while one ceramic coating provided excellent protection and demonstrated the ability to prevent corrosion even though the coating was severely chipped. Chemically deposited nickel gave adequate protection in the cooler midchord regions of the blade. Nickel over a Nicrobraz undercoating gave excellent protection over the most difficult of all regions, that is, the leading edge. Nicrobraz provided excellent protection over the entire blade.

INTRODUCTION

Turbine cooling research being conducted by the NACA Lewis laboratory includes work directed toward the development of air-cooled turbine rotor blades of nonstrategic metals that can be operated in turbojet engines at present-day or slightly higher gas-temperature levels. The

cooling effectiveness of each of a variety of air-cooled turbine blades has been investigated in turbojet engines that were modified to accommodate either two or four air-cooled blades (refs. 1 to 7). These investigations indicated that blades of nonstrategic metals can be cooled sufficiently at ratios of coolant flow to combustion-gas flow of 0.02 to 0.05 to make their use feasible at present-day operating conditions. Endurance running of 12 blades of SAE 4130 or Timken 17-22A(S) steels (roughly 97 and 96 percent iron, respectively)(ref. 8) showed these blades to be capable of extended operation at current gas temperature levels. However, corrosion of the blade shell became evident within 5 hours and limited experimental blade life to roughly 50 hours at maximum engine speed and gas temperature, thus emphasizing the need for the inhibition of corrosion. 2880

Preliminary endurance investigations in a turbojet engine of nickel and ceramic coatings on blades of nonstrategic metals (ref. 9) indicated that nickel provided adequate corrosion protection over the major portions of such blades for about 25 hours at rated maximum turbine speed and inlet gas temperature but would not protect the leading edge for more than 10 hours. The two ceramic coatings investigated did not provide protection for even 5 hours.

This report concerns itself with the endurance testing of four promising types of corrosion-resistant coatings. Ceramic, nickel, aluminized, and Nicrobraz coatings were applied to blade shells of either SAE 4130 or Timken 17-22A(S) steel and a total of 20 blades was run at the maximum rated engine speed of 11,500 rpm (1300 ft/sec tip speed) with a constant turbine inlet temperature of approximately 1670° F. The ratio of coolant flow to combustion-gas flow per blade (hereinafter called coolant-flow ratio) was maintained constant, usually at 0.048, although, in a few cases, flow ratios of 0.038 and 0.030 were used.

The goal of the endurance tests was arbitrarily set at 100 hours at maximum rated conditions in view of the lack of any standard test for coated blade life. In normal flight service, the engine may not be subjected continuously to maximum rated speed (and its attendant gas temperature) for more than 30 minutes at a time.

For convenience, the results of the previous preliminary investigation of nine coated nonstrategic blades (ref. 9) are summarized in this report.

Acknowledgement is made of the cooperation received from the California Metal Enameling Company, The Calorizing Company, the Ferro Corporation, the Research Laboratories Division of General Motors Corporation, and the Solar Aircraft Company in the application of various types of coatings to the air-cooled turbine blades.

COATINGS

General Requirements

A protective coating for application to air-cooled nonstrategic turbine blades must be able to withstand the corrosive and erosive action of the high-temperature, high-velocity combustion-gas stream to which the blades are subjected in a turbojet engine. Any protective coating applied to such a blade must adhere well to the blade when operating at high temperatures under the influence of high centrifugal forces. The coating must be able to withstand the thermal shocks to which the turbine blade is subjected during the starting and stopping of the engine and the rapid changes in blade temperature that may occur during other transient conditions that are incident to normal engine operation. The coefficient of thermal expansion of the coating must be sufficiently close to that of the blade metal over a range of temperatures to prevent spalling and flaking of the coating. The coating must have sufficient ductility to withstand the vibration and the elongation of the turbine blade that occur during engine operation. The coating should be capable of withstanding normal handling. Its presence on the blade surface should not seriously affect the tensile or fatigue strength of the blade shell. Its application should not adversely affect or restrict the heat-treatment procedures that are required to develop the necessary physical properties of the blade metal. It is also desirable that the coating protect the walls of the coolant passages as well as the outer surface of the blade.

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Although the metal shell of an air-cooled turbine blade is considerably cooler than the combustion gas, the temperature level is still relatively high. Experimental chordwise temperature distributions in the shells of air-cooled turbine blades of profiles A and B (see fig. 1) for coolant-flow ratios of 0.05 and 0.03 are shown in figure 2. Although these temperature distributions were obtained for specific air-cooled blades operating in a particular turbojet engine, they are indicative of the temperature levels at which metals and coatings for forced-convection air-cooled turbine blades might operate in present-day turbojet engines. It may be seen that leading and trailing edges operate at temperatures as high as 1200° F, while the midchord regions are 200° to 300° F cooler.

The blade temperatures shown in figure 2 for profile B are somewhat higher than those reported in reference 9 for the same profile. The values of figure 2 are based on more comprehensive experimental data.

Types of Coatings

In this investigation, nonstrategic air-cooled turbine blades were coated with ceramics, nickel, or Nicrobraz while others were aluminized. A brief summary of the reasons for selecting these coatings for application to cooled turbine blades and of the general procedures involved in applying the coatings is given in the following paragraphs. 2880

Ceramic coatings. - The successful use of ceramic coatings to inhibit corrosion in numerous high-temperature applications in order to prolong life and/or to reduce the strategic metal content led to the consideration of such coatings for air-cooled nonstrategic turbine blades.

In addition to the general requirements outlined previously, a ceramic coating should be as thin as practical in order to keep the shear stresses at the bonding surface to a minimum and to obtain improved resistance to thermal shock. Thin coatings also show less susceptibility to chipping through mishandling (ref. 10).

In preparing ceramics for coatings, the proper proportions of materials (generally metal oxides and fluxing agents) are fused and quenched in water. The resulting substances, along with additions made to control certain physical properties, are ground in liquid (usually water) and applied to the metal surfaces by spraying or dipping. The coating, which may be as thin as 0.001 to 0.002 inch, is dried at 200° to 250° F and then fired. Firing temperatures vary widely; at the higher temperatures metallurgical effects upon the metal being coated must be considered when stress-rupture properties are important. Coating the interior surfaces of restricted regions with ceramic presents difficulties which must be considered carefully, particularly in cases such as the blades of the present investigation where blockage of the cooling-air passages is intolerable.

Nickel coatings. - For many years ferrous metals have been successfully protected from corrosion by plating with various corrosion-resistant metals such as nickel, chromium, silver, and cadmium. The plating material used depends greatly upon the environment and service to which the plated part will be exposed. Of the more corrosion-resistant metals, nickel is one of the most common applied to steel and appears to be well suited for use on turbine blades. For applying nickel coatings to the experimental blades, chemical deposition was selected in preference to electroplating for two reasons: first, electroplating will not coat the inner heat-transfer surfaces of the blades, and

second, setting up equipment to coat small numbers of blades is simpler for the chemical process. The hardness of chemically deposited nickel is greater than that of electrodeposited nickel. As applied, the chemically deposited nickel is brittle but upon heating becomes ductile and, at the same time, increases in hardness (ref. 11).

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The chemical deposition method involves dipping the blade in an acid solution containing nickel chloride or nickel sulfate and other chemicals. Table I summarizes the composition of the two acid-nickel baths used in plating blades for this investigation. The solution is generally maintained in the temperature range of 150° to 200° F. The relatively low temperature of the solution in no way influences the heat treatment that may have been given the blade prior to the plating process. The time required to form a coating 0.001 to 0.0015 inch thick is of the order of 1 to 4 hours. Reference 11 gives a detailed account of the methods and procedures involved in applying chemically deposited nickel to steel.

Nicrobraz coatings. - Nicrobraz is the trade name of a commerical brazing compound composed of about 72.3 percent nickel, 15 percent chromium, 3.75 percent boron, 4.5 percent silicon, 4.0 percent iron, and 0.45 percent carbon. It produces a hard, corrosion-resistant coating when fused and cooled. Its successful use in brazing the blade shell to the base and the observation of its subsequent behavior in service led to its trial as a coating.

In order to coat a steel surface, Nicrobraz in powder form may be suspended in a 10 percent calcium chloride solution, brushed on the surface, and allowed to dry. When heated in a dry hydrogen atmosphere to a temperature of about 2075° F, the Nicrobraz will fuse to the surface to form a hard continuous layer.

Aluminized coatings. - Aluminum coatings have been used for many years to protect low alloy steels from corrosion (ref. 12, pp. 703-704 and ref. 13, pp. 704-705). The aluminum may be either in the form of a coating of the pure metal or as an alloyed aluminum-iron layer varying from a few thousandths of an inch to more than 0.050 inch in thickness. This method of protection is known as aluminizing. Usually aluminized parts are limited to operating temperatures of about 1500° F, but short-time service up to 1750° F has been obtained (ref. 12).

There are two general methods by which steels are aluminized, namely, the "pack" process and the "dip" process. Both these processes were used to aluminize turbine blades for this investigation. The important features of each method are summarized in the following paragraphs.

Pack process: In the pack process the part to be aluminized is packed in a box containing powdered aluminum and a small amount of

ammonium chloride. The box is then sealed gastight and heated to a temperature of 1500° to 1800° F for about 6 to 24 hours. This process impregnates the surface layer of the metal with aluminum and also imparts a heat treatment to the parent metal. The temperature-time relation for the aluminizing process depends upon the size of the part and the amount of aluminum penetration desired. The depth of aluminum penetration can be varied as desired; values usually range from 0.005 to 0.040 inch. The surface layer of iron-aluminum alloy usually contains about 25 percent aluminum, which results in good resistance to heat and corrosion and also exhibits good toughness and ductility characteristics. A more detailed account of the pack process is given in reference 12.

Dip process: In the dip process the part to be aluminized is cleaned, dipped in molten aluminum for a controlled time, and, if desired, suitably heat treated to permit diffusion of the aluminum into the steel. For parts that are to operate at temperatures exceeding 1000° F the time and temperature of the aluminum dip must be closely controlled (ref. 14). Dip temperatures are of the order of 1300° F and dip periods range from 15 seconds to 6 minutes (ref. 14). The iron-aluminum alloy formed during the immersion of the steel in molten aluminum is extremely hard and brittle and contains about 55 percent aluminum. In order to develop a surface layer that is softer and less brittle and that resists spalling and cracking, a diffusion heat treatment is given after the dipping. The diffusion heat treatment is carried out at a temperature of about 1800° F for times varying from 1 to 6 hours. The exact diffusion heat-treatment time required depends upon the chemical content of the steel and the dipping time in the molten aluminum. Reference 14 describes a patented commerical aluminum-dip process.

Both the pack process and the dip process involve heating of the aluminized part for extended periods of time at temperatures of 1500° to 1800° F, which may adversely affect the physical properties of the parent metal for turbine blade application. The interior surfaces of the blade may be aluminized by either process.

APPARATUS AND INSTRUMENTATION

Preparation of Coated Air-Cooled Blades

Blade construction. - All the coated air-cooled turbine blades reported herein were of the shell-supported type where the load is carried by the blade shell. The span was 4 inches and the chord, approximately $1\frac{7}{8}$ inches. All the blades were nontwisted except blade 4, which was given a twist to approximate that of the uncooled blades. The shells of all blades except blade 1 were formed by contour pressing seamless tapered-wall tubes into the desired airfoil shape; blade 1 was cast. The

shell material used in these blades was either SAE 4130 or Timken 17-22A(S) steel. These steels were selected because stress-rupture data for the metal temperature range in which these air-cooled blades were to operate indicated that these metals were best suited of the readily available nonstrategic steels. All the blade bases were made of cast SAE 4130 steel. Table II indicates the shell material of each blade.

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The internal heat-transfer areas of all blades were increased by brazing mild steel tubes to the inner surfaces of the shells, as shown in figure 1. Copper was used as a braze material for all blades except numbers 26 through 29; Nicrobraz was substituted in these blades because copper would be attacked by molten aluminum during the aluminizing process.

Blade fabrication procedures are discussed in detail in reference 15.

The three blade profiles used in this investigation are shown in figure 1. The root profiles are the same as the tip, except for a slight change in the outside contour because of the tapered wall of the shell. Profiles A and B (figs. 1(a) and 1(b), respectively) were obtained by forming the shells, and profile C (fig. 1(c)) was obtained by casting. Profiles A and C are essentially the same and are nearly equivalent to the root profile of the standard uncooled turbine blade used in the test engine. Profile B was an airfoil section which was designed to operate in a completely air-cooled turbine rotor with twisted stator blades. Table II indicates the profile of each blade. The various blades used were selected because they were readily available from other investigations and thereby reduced the time required to prepare for the coating investigation.

Blade coatings and heat treatments. - The coatings and heat treatments applied to the individual experimental blades follow. Heat treatments were selected on the basis of available data to obtain the best stress-rupture properties of the metal used and were modified as additional data and operating experience were gained.

Ceramic-coated blades: Five experimental blades were ceramic coated for this investigation by commercial concerns; the compositions of the coatings and the details of their application were considered proprietary information and were not revealed. Blades 1 and 2 (blades 7 and 8 of ref. 9) were coated with a modification of National Bureau of Standards' A-19 coating and were not heat-treated for fear of damaging the coatings. Blade 3 was coated with Solaramic 8042/3FE and subsequently heat treated as indicated in tables II and III by the NACA after consultation with the coating vendor as to the limitations imposed by the ceramic.

Blades 4 and 5 were coated with another modification of NBS A-19 coating and heat treated as indicated in tables II and III. All ceramic coatings were applied to only the outside surfaces of the blade shell.

Nickel-coated blades: Nickel coatings were applied to blades 6 through 11 by the NACA using solution 1 of table I and to blades 12 through 15 by a commercial concern using solution 2 of table I. No difference in the coatings was noted. The inner surfaces of the blades were nickel coated in each case. All blades were heat treated as indicated in tables II and III prior to coating.

Nickel- and Nicrobraz-coated blades: A combination nickel and Nicrobraz coating was employed on blades 16 through 20. A Nicrobraz coating was applied to the leading edge and the entire airfoil section was subsequently nickel coated. The indicated heat treatment (table II) was combined with the Nicrobraz coating operation.

Nicrobraz coatings: Nicrobraz was used to coat the entire airfoil sections of blades 21, 22, and 23. Again, the indicated heat treatment was combined with the coating operation.

Aluminized blades: Six aluminized blades were obtained for this investigation, two were aluminized by the pack process and four by the dip process. Both processes aluminized the inner heat-transfer surfaces of the blades. The pack process was used on blades 24 and 25; the blades were packed in aluminum oxide, aluminum powder, and an energizer for 12 hours at 1800° F. Blades 26 through 29 were aluminized by the dip process. They were preheated in a salt flux at 1320° F for 5 minutes, dipped in molten aluminum at 1300° F for 30 seconds, washed in molten salt at 1320° F for 30 seconds, air cooled, washed, and heat treated as indicated in tables II and III. The heat treatment permitted the desired diffusion of the aluminum into the steel. Fillets were applied at the roots of blades 26 through 29 after aluminizing to reduce stress concentrations in those regions. In the process, the coatings in the adjacent areas were damaged slightly.

Engines. - Several production turbojet engines were modified to allow cooling air to be supplied to either two or four experimental turbine rotor blades. The modifications were essentially those described in reference 1. An adjustable tail-pipe nozzle was used to regulate turbine gas temperatures. Blade cooling air was supplied from a compressed-air system external to the engine. Effective gas temperatures at the turbine blades were measured by chromel-alumel thermocouples buried in the leading edges of standard uncooled blades at a section $2\frac{9}{16}$ inches from the blade tip. No thermocouples were installed on cooled blades. Details of the thermocouple installation are given in reference 1.

PROCEDURE

For an evaluation of the effectiveness of the various protective coatings, two types of engine operation have been employed - constant-speed and cyclic operation. In constant-speed running, the engine was operated at maximum rated speed (11,500 rpm) with the tail-pipe nozzle adjusted to obtain an effective gas (or uncooled blade) temperature of 1450° F, which corresponds to approximately a 1670° F turbine inlet gas temperature. Cooling-air temperatures at the base of the blade were about 180° F. These conditions will hereinafter be designated rated test conditions. The coolant-flow ratio was set at the desired level once engine speed and gas temperature were established. Conditions were then maintained constant for the duration of the endurance run.

Cyclic tests consisted of operation at the rated test conditions for 15 minutes and then at idling speed (4000 rpm) for 5 minutes with no change in either cooling-air flow controls or tail-pipe nozzle position. The engine was then accelerated to rated speed and the cycle repeated. Accelerating and decelerating periods were of the order of 15 seconds.

Blades 1, 8, 9, 10, and 11, which were first reported in reference 9, were subjected to cyclic engine operation. All other blades were subjected to steady-speed operation. Table II indicates the type and amount of running time accumulated on each blade. Cyclic operation was found to be very severe on engine components and excessive amounts of time were required for engine repair and maintenance. In order to expedite the investigation of coatings the cyclic type of operation was discontinued in favor of the steady-speed running. It was believed that the steady-speed operation subjected the coated blades to a sufficient number of rapid temperature changes during the starting and shut-down operations to demonstrate the ability of a coating to withstand repeated thermal shock.

For flight application, the maximum engine speed for continuous operation is 11,000 rpm, while operation at 11,500 rpm is limited to half-hour periods for take-off or combat. The NACA test speed was set at 11,500 rpm. Tail-pipe temperatures in service are limited to 1292° F except for starting and accelerating; the NACA, in maintaining a constant uncooled blade (or effective gas) temperature of 1450° F, encountered tail-pipe temperatures ranging from 1280° to 1350° F, depending on ambient conditions and the condition of the equipment being used, with 1325° F being typical of most of the operation.

During the course of the coating investigation, the coated blades were often damaged by failure of uncooled blades or of other air-cooled blades or by some object which passed through the turbine. There were instances where coated blades failed in rupture while the coating was in good condition. Such failures, which resulted from causes not related to the coatings, will hereinafter be referred to as mechanical failures. In many cases, the damage to the experimental blade was confined to the tip region and the major portion of the blade could be salvaged and used for further testing. While centrifugal stresses were reduced and the vibrational characteristics were changed, it was felt that, insofar as coating durability was concerned, the results from such blades would not be altered appreciably.

RESULTS AND DISCUSSION

The results of endurance investigations on several types of corrosion-resistant coatings applied to air-cooled turbine blades of SAE 4130 or Timken 17-22A(S) steel are reported in the ensuing section and are summarized in table II.

Ceramic Coatings

Five ceramic-coated blades were endurance-tested. Two coating failures were encountered and blade failures from causes not connected with their coatings terminated the tests on two others before any significant amount of running could be obtained. The fifth blade successfully completed 100 hours of operation at the rated test conditions.

Blade 1. - The coating on blade 1 was considered a failure after 7.3 hours of rated engine speed operation, and investigation of the blade was concluded at the end of that time. Figure 3(a) shows several views of the blade at the conclusion of the tests and it can be seen that the coating chipped away from the leading- and trailing-edge regions of the blade. There is also an area near the root in the midchord region of

the blade where the coating flaked off. The failure of the coating apparently was a function of the metal temperature, as the greatest damage to the coating occurred at the leading- and trailing-edge regions where the metal temperatures are the highest (see fig. 2). More coating was removed from the leading edge than from the trailing edge, probably because the high-velocity combustion gases impinge directly upon the leading edge and their erosive action is greatest in this area.

Blade 2. - Blade 2 was considered a failure after about 4.7 hours of operation. Inspection at this time indicated that the coating apparently softened when heated and flowed toward the blade tip under the influence of the high centrifugal forces. A photograph of this blade is shown in figure 3(b). The flow lines were essentially parallel to the blade base over the relatively cool midchord region on both the pressure and suction surfaces. In the leading- and trailing-edge regions, which operate hotter than the midchord region, the flow lines were nearly radial and were very pronounced as shown in figure 3(b). Bare metal was visible in the valleys between flow lines in the leading- and trailing-edge areas. Inasmuch as the blade was not heat-treated, there was no possibility of damage from this source, and it must be assumed that the coating lacked the necessary physical properties for the application in question.

Blade 3. - Blade 3 was given heat treatment 5 of table III. This heat treatment was specified and applied to the blade by the NACA after correspondence with the coating supplier relative to the restrictions imposed on the process by the ceramic coating. After the blade was heat-treated, the coating was discolored in scattered areas and may have been damaged. Nevertheless the blade was tested to see whether the damage would progress. After 8 hours of operation the blade was inspected and the coating appeared to be in as good condition as when the test began. Operation was continued and at 11.3 hours damage to the cooling-air supply system resulted in the air-cooled blade overheating and fracturing at a section about 1/3 span from the root. The coating on the remaining 1/3 of the blade appeared to be in the same condition as when the test began except for slight evidence of erosion at the leading edge. Although no definite conclusions could be made regarding the durability of this coating, it appeared promising.

Blades 4 and 5. - Blades 4 and 5 were both coated with the same ceramic, a modified NBS A-19 type coating, and were given heat treatment 1 (table III) by the coating supplier. Inspection of the blades after 8.3 hours of operation indicated that both were in excellent condition. Blade 4 failed in fatigue at the root shortly after this inspection and the tests were continued with blade 5 only. At approximately 20 hours operation a foreign object passed through the turbine and struck blade 5, with the result that a portion of the coating along the leading edge of

the blade was chipped off and bare metal appeared to be exposed. Operation was continued, however, and after 34.3 hours the blade was again struck by a foreign object and damaged in about the same area as previously. This damage can be seen on the leading edge of the blade in figure 4(a). Several smaller chipped areas were observed in the coating on the forward portion of the suction surface near the blade tip and can also be seen in figure 4(a). Investigation of the coating was continued until the blade was operated for 100 hours at rated test conditions. Figure 4(b) shows the blade upon completion of 100 hours of operation. (The damage to the coating along the trailing edge of the blade which is visible in the view of the pressure surface in fig. 4(b) was caused by mishandling of the blade after completion of the tests.) Microscopic examination of a section through the damaged area at the leading edge indicated that some ceramic still clung to the metal and apparently provided complete corrosion protection since no corrosion could be observed under the microscope. During the investigation of blade 5 no softening or flowing of the coating was observed. No chipping or flaking other than that caused by foreign particles passing through the turbine was observed. Slightly raised markings that became evident on the surface of the coating after heat treating were still visible after 100 hours of running, indicating that the coating had not eroded to any great extent. After 100 hours of operation the coating was in excellent condition except where it had been hit and appeared to provide complete protection for the blade shell even in those areas. Corrosion was observed on the uncoated inner surfaces of the shell and on the cooling-air tubes to depths of 0.003 to 0.005 inch. These observations were made in the immediate vicinity of the leading edge.

The investigation of five ceramic-coated turbine blades indicates that a ceramic coating is capable of providing corrosion protection to an air-cooled blade of SAE 4130 steel for 100 hours of operation at speeds and temperatures equal to or more severe than those encountered at maximum rated conditions in a present-day turbojet engine. Whether this coating would also provide satisfactory protection for Timken 17-22A(S) material is not definitely known; the coating supplier believes, however, that Timken 17-22A(S) can be successfully coated with perhaps slight modification of the coating and the application procedure. The ability of this coating to adhere and provide protection after severe chipping is significant and is a very desirable characteristic for a ceramic coating for turbine blade application. The coating on blade 3 appeared to be promising, although the short endurance test given here makes further work necessary before definite conclusions can be reached.

Nickel Coatings

Ten nickel-coated blades (blades 6 through 15) and five blades having a combination of nickel and Nicrobraz coatings (blades 16

through 20) were investigated. Seven of these blades had SAE 4130 steel shells and eight blades had shells of Timken 17-22A(S) steel.

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Blades 6 through 15. - Of the ten blades that depended entirely on nickel coating for corrosion protection, blades 6, 8, 9, 11, 12, 14, and 15 operated for sufficient lengths of time to obtain significant coating results. Blades 7, 10, and 13 failed mechanically and investigation of the coatings on these blades was terminated after short periods of time, as shown in table II. The last inspections of the coatings of these three blades prior to their mechanical failure indicated the coatings were still in good condition.

Blades 6, 8, 9, 11, 12, 14, and 15 were operated at rated test conditions for periods of time ranging from about 11.5 hours to as much as 25 hours before the coatings were considered failures. The failures of the nickel coatings were all similar, that is, the nickel began to blister and chip away from the leading- and trailing-edge regions of the blades as shown in figure 5(a). As operation of the blades was continued, corrosion of the parent metal in the leading and trailing edges occurred and the nickel coating also began to fail in the midchord region of the blade. The coatings generally began to fail first in the tip region of the blade after about 11 to 15 hours of rated engine speed operation. Temperature and centrifugal force are both factors in the breakdown of the coating. Failure usually progressed rapidly along the leading edge of the blade, where erosion also seemed to be a factor in removal of the coating. A blade that exhibited extensive erosion and corrosion at the leading edge is shown in figure 5(b), which is a photograph of blade 6 at the completion of 44 hours at rated test conditions. The failure of the coating along the trailing edge was generally less extensive than that at the leading edge, probably because the scouring action of the combustion gases is not so great in this region. Also, trailing-edge temperatures are somewhat lower than those at the leading edge. The temperature level of the blade material influences the life of the nickel coating; failure of the coating in the cooler midchord region was much more infrequent than at the leading and trailing edges (see fig. 2). Frequently, no evidence of failure was observed in the midchord region. The lower temperature apparently enables the nickel to adhere and provide the necessary corrosion resistance.

Blades 16 through 20. - Because investigation of blades 6 through 15 indicated that the nickel coating generally failed initially in the leading-edge region and that this failure appeared to be caused by corrosion and erosion, it was thought that a corrosion-resistant material, harder than nickel, should be applied to the leading edge of the blade. The balance of the blade surface (except perhaps the trailing edge) might then be adequately protected by a nickel coating. Five such blades (blades 16 through 20) were prepared. A Nicrobraz coating was first applied to the leading-edge region of the blades as described in the

PROCEDURE section of this report. The blades were then nickel-coated, and in this manner the Nicrobraz formed an undercoat for the nickel along the leading edge.

Blades 17 and 18 failed in fatigue at the blade root after 11.4 and 23.7 hours of operation, respectively. The coatings were in good condition at the inspections prior to the time of the fatigue failures. Blade 19 was damaged beyond repair by fragments from a failed blade after 25.6 hours of operation. The coating on this blade had shown evidence of slight flaking in the midchord region near the tip, but the coating on the rest of the blade was in good condition prior to the time the blade was damaged. Blades 16 and 20 were operated successfully for 101.2 and 100 hours, respectively. The coating on blade 16 was in good condition except for scaling of the nickel on the rear third of the suction surface. No corrosion of the blade metal was apparent in this area. At the end of 100 hours of operation on blade 20 the coating was in excellent condition except for a small area on the pressure surface near the trailing edge where the coating had begun to flake off (fig. 6). No corrosion of the parent metal was observed. In the leading-edge region near the tip on the suction surface of blade 20 there appeared to be several small areas where the nickel had flaked away. This damage was caused by foreign particles passing through the engine which struck the blade in the leading-edge region where there was a Nicrobraz undercoat, and, although the nickel chipped away, the Nicrobraz protected the parent metal. The adherence of the nickel to the Nicrobraz appeared to eliminate flaking of the nickel and enabled it to protect the blade. The underlying Nicrobraz, while capable of providing protection, was not called upon to do so except where the nickel was chipped away by foreign particles striking the blade.

During the investigation of the five nickel-coated blades having Nicrobraz undercoat at the leading edges, none of the tests were terminated because of coating failure. Adherence of the nickel over the entire blade appeared to be better in this group of blades than in those previously employed. Blades 16 through 20 had shells of Timken 17-22A(S) steel; while the previous group, with the exception of blades 7 and 8, had shells of SAE 4130 steel (see table II). Based solely on observation of these blades, it appears that the adherence of nickel, when applied in the manner previously described, is greater to Timken 17-22A(S) steel than to SAE 4130 steel.

Nicrobraz Coatings

Blades 21, 22, and 23. - Because of the success obtained in using Nicrobraz as an undercoat for nickel, it was believed that a completely

Nicrobraz-coated blade might operate successfully. Furthermore, the ease with which a Nicrobraz coating can be applied and the fact that its application can be combined with other brazing operations during blade fabrication made the Nicrobraz coating appear desirable. Consequently, blades 21, 22, and 23 were Nicrobraz-coated.

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Blade 21 successfully completed 100 hours of operation at rated test conditions with a coolant-flow ratio of 0.048 but failed mechanically after an additional 1.2 hours of operation at a flow ratio of 0.03. The Nicrobraz coating was in excellent condition after 100 hours and showed no evidence of impending failure. Blades 22 and 23 were operated for 31.5 and 5.9 hours, respectively. Both blades failed in fatigue at the blade root. Prior to failure the coatings on both blades were in excellent condition.

This investigation indicates that Nicrobraz coatings provide good corrosion and erosion protection for Timken 17-22A(S) steel. It is believed that Nicrobraz would offer similar protection to SAE 4130 steel. Nicrobraz possesses strong alloying characteristics and may penetrate the parent metal to some degree; its effect on the fatigue strength of the blade shell remains to be determined.

Aluminized Coatings

Blades 24 and 25. - Blades 24 and 25 were aluminized by the pack process. Blade 24 successfully completed 100 hours of operation and the aluminized coating was in excellent condition at the completion of running. Slight erosion of the leading-edge surface was noted, but it was not extensive and no evidence of corrosion was observed. The midchord and trailing-edge regions of the blade showed no evidences of erosion or corrosion. Blade 25 failed structurally after 8 hours of operation; the blade surface was in excellent condition until that time.

The suction surface of blade 24 was struck by fragments of a failed blade after 50 hours of operation and a number of shallow scratches resulted (see fig. 7(a)). The aluminized layer was sufficiently tough to withstand the impact and no damage was sustained other than the scratches themselves. Upon further running the scratches disappeared and were presumably filled in by iron-aluminum compounds from the adjacent surfaces. The surface of the blade after an additional 50 hours of operation showed no traces of the damage (see fig. 7(b)).

The surfaces of blades 24 and 25 were considerably rougher after aluminizing than they were prior to being coated. This roughness did not change with operating time. This surface roughness is typical of blades aluminized by the pack process.

Before operation the color of the blade surface was deep gray. After operation, blade 24 exhibited a reddish color along the leading edge, over most of the suction surface, and over about 20 percent of the pressure surface. This change in color is apparently typical and is the result of the formation of complex iron-aluminum oxides which provide a protective, adherent refractory coating on the surface of aluminized steels (ref. 14). 2880

Blades 26 through 29. - Blades 26 through 29 were aluminized by the dip process; all the blades were operated successfully for a minimum of 100 hours at rated test conditions as shown in table II. Blades 26 and 27 were operated for 124.4 hours. The coatings on all the blades were in excellent condition at the conclusion of the tests. All the blades of this group were damaged during the course of the investigation by several mechanical failures; in order to continue investigation of the coatings the tips of the blades were ground off. The blades were therefore shorter than normal, particularly blades 26, 27, and 28, as shown in figure 8. The shortening of the blades resulted in lower stresses in the blades shells, but this would not be expected to affect the life of the coatings appreciably. Any possible weakening of the parent metal as a result of the aluminizing treatment would, of course, not show up so readily.

The surfaces of the blades that were aluminized by the dip process were only slightly rougher after aluminizing than before being coated, and the surfaces of this group of blades were considerably smoother than those aluminized by the pack process. After aluminizing the color of the blade surfaces was a deep grey. During operation the blade surfaces developed a reddish-orange color over most of the blade. This was similar to the color observed on blades 24 and 25.

Figure 8(a) shows the suction surfaces of blades 26, 27, and 28 early in the investigation and of blade 29 prior to operation. Figure 8(b) shows both the pressure and suction surfaces of the blades at the completion of the investigation. Comparison of the suction surfaces shown in figures 8(a) and 8(b) indicates that there was little change in the condition of the coating on the blades, even though the blades of figure 8(b) have about 100 hours more operating time than in figure 8(a). With one exception, the entire surface of each blade including the leading- and trailing-edge regions, which were the first to exhibit failures on the ceramic and nickel coatings, was in excellent condition at the completion of the tests. Surface scratches and abrasions showed no tendency to progress and no corrosion developed in them as the investigation continued. The tip regions of blades 26 and 27 were damaged when struck by fragments of another blade, but the aluminized coatings continued to protect the surrounding areas. No corrosion was evident except on blade 27, where the metal was actually torn and the bare steel was exposed to the action of the gases.

The one exception to the general excellent condition of the blade surfaces was along the leading edge of blade 28, where several short, fine cracks were visible to the unaided eye. The surfaces from the leading edge as far back as the first cooling-air tube were a different color from the rest of the blade, being a muddy gray without red or orange tinges noted elsewhere on the same blade and on the other blades of this group, including the leading edges. Examination showed that the cooling passage along the leading edge had been almost completely blocked by loose scale, presumably from the external cooling-air system, which had wedged into a restricted region at the blade root. Complete blockage would have given a leading-edge temperature of the order of 1400° F. Microscopic examination of sections along the leading edge and at 90° to the leading edge about 1.8 inches from the blade base brought out the following facts: The Timken 17-22A(S) steel in the leading-edge region of the blade shell had softened because of its higher temperature; the hardness near the leading edge was less than Rockwell C-10 as contrasted with Rockwell C-28 in the region opposite the first cooling tube. The coating at the leading edge showed a Rockwell C-19 hardness as compared with a C-28 hardness opposite the first cooling-air tube. The aluminized layer contained a series of fine cracks over the entire section. In the cooler region near the cooling-air tubes, these were hairline cracks which did not penetrate the coatings; near the leading edge they occurred with about the same frequency but were heavier and sometimes penetrated the aluminized layer. When the coating was penetrated, a corroded region mushroomed out from the crack into the underlying steel. At the section examined the coating was thicker on the inside than on the exterior of the blade shell; possibly the greater erosive action of the exhaust gases accounts for this effect. The SAE 1020 steel cooling-air tubes of blade 28 were aluminized almost completely through; the aluminum penetrated all except a 0.001- to 0.0015-inch-thick region in the center of the tube wall.

The coatings in the root regions of this group of blades were rough and the blades themselves appear to be damaged. This condition arose when the fillets were applied at the blade roots subsequent to the aluminizing operation. The affected areas did not increase in size as the endurance operation progressed and the blade shells were protected adequately. Within the filleted area itself, however, the shell of blade 28 was damaged, presumably during the filleting process, and cracks developed after 118 hours of operation; reducing the blade length by cutting off damaged portions near the tip undoubtedly forestalled an early blade failure in this case.

The work with aluminized blades indicates that aluminizing is a satisfactory method of protecting Timken 17-22A(S) turbine blades in present-day turbojet engines at maximum rated conditions with blade temperatures up to 1200° F. Under the conditions of operation, the coating apparently breaks down at metal temperatures between 1200° and about 1400° F.

[redacted]

General Comments

It has been demonstrated that air-cooled turbine blades of nonstrategic steels can be successfully operated in a turbojet engine for extended periods of time with reasonable cooling-air flow rates when protected by ceramic, nickel-Nicrobraz, Nicrobraz, or aluminized coatings. It is believed, however, that more research is required before any of these protective coatings can be specifically recommended for service use in a turbojet engine.

The endurance life of a nonstrategic turbine blade depends not only on the durability of the coating but also on the fatigue strength, creep, and stress-rupture properties of the parent material at elevated temperatures. The effects of the various coatings on these properties are not entirely known at the present time.

The depth of penetration of ceramic coatings into the parent metal is barely measurable and, it is believed at this time, can be neglected insofar as any effect on the strength properties of the blade is concerned. The limitations that a given ceramic coating may impose upon the heat treatment of a steel are an important consideration, however. The mechanical failure of blades 1 and 10 can be attributed to the absence of heat treatment (see remarks of table II). From the limited experience attained with the ceramic-coated blades of this investigation, it appears to be desirable to use a coating whose firing temperature is about the same as or lower than that of the desired normalizing temperature, so that the heat-treat and firing operations can be combined. This is not only convenient, but may be necessary to avoid detrimental effects to the ceramic coating that may result when the heat treatment is a subsequent operation or to the metal properties when the ceramic is fired after the blade is heat treated.

The nickel coating on blades having nickel or nickel-Nicrobraz coatings does not penetrate the parent metal significantly and would not be expected to influence the strength or creep properties of the blade shell.

Nicrobraz alloys readily with steels and undoubtedly affects their stress-rupture and fatigue properties. However, such data are not available. It is believed that the high percentage of fatigue failures on blades 16 through 23 was due to fabrication techniques rather than detrimental effects of the Nicrobraz on the metal of the blade shells.

When blades are aluminized they must be heated to 1500° F or higher for several hours in order to diffuse the aluminum properly. In the case of SAE 4130 and Timken 17-22A(S) steels, extended heating at temperatures above about 1750° F may adversely affect their strengths. Aluminized steel, of course, has a layer of iron-aluminum alloy at the surface. What effect, if any, this alloy layer may have upon the strength of the steel, particularly in thin walls such as used in the shells of turbine blades, is not known.

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It is obvious that before any coating can be recommended for service use its effects on the physical properties of the blade metal must be known.

The importance of providing protection over the interior surfaces of the blades was brought out in a number of cases during this investigation. Corrosion was noted on the mild steel cooling-air tubes of blades after three or four days exposure to the atmosphere, even when those blades had not been operated in an engine. After 100 hours of operation, corrosion to a depth about 0.005 inch was noted in the leading-edge region of blade 5 on the uncoated inner surface; in thin shells of air-cooled blades, corrosion to this depth will have an appreciable effect on the strength of the blade. In more destructive atmospheres, such as encountered in carrier-based operations, corrosion will be more severe and the need for protection correspondingly greater.

SUMMARY OF RESULTS

The results of an experimental investigation to determine the durability of several protective coatings applied to nonstrategic air-cooled turbine blades which were operated in a turbojet engine are as follows:

1. Satisfactory protection of the blades was provided by ceramic, nickel-Nicrobraz, Nicrobraz, and aluminized coatings. Each of these coatings indicated that it would give satisfactory corrosion and erosion protection to the turbine blades for 100 hours of maximum rated engine speed operation with coolant-flow ratios in the range of 0.030 to 0.048. However, the adherence of the nickel was erratic and unpredictable.

2. Blades aluminized by the pack and by the dip-and-diffusion processes gave excellent protection against oxidation and corrosion. All the aluminized blades (except one that failed mechanically) operated for at least 100 hours. Two blades were run for 124.4 hours and were in excellent condition when the tests were terminated.

3. One ceramic coating (a modified NBS A-19 ceramic) provided excellent service. This coating, although seemingly chipped completely through in certain regions by foreign particles striking the blade, was sufficiently adherent to leave a thin film which gave satisfactory protection to the underlying metal over an extended period of operation.

4. Chemically deposited nickel coatings were found to require an undercoating of some type at the leading edge of the blade in order to

prevent flaking and failure of the nickel in this region of the blade. A Nicrobraz undercoat provided a satisfactory base for the nickel at the leading edge. Blades having a Nicrobraz undercoat at the leading edge and a chemically deposited nickel coating over the entire blade surface gave adequate protection for 100 hours of rated engine speed operation. However, the nickel coatings in this investigation were erratic insofar as adherence was concerned and often failed in much shorter periods.

5. Nicrobraz coatings applied to the leading edge or to the entire blade surface exhibited very satisfactory corrosion-resistant properties. 2880

6. Aluminum and Nicrobraz alloy with and undoubtedly affect to some extent the fatigue strength and stress-to-rupture properties of the metals to which they are applied. Application of the aluminum or Nicrobraz coatings may result in overheating the parent metal prior to heat treatment. The effects of these various factors on the strength of the blade shell are not known at the present time, but they should be evaluated before any protective coating is considered for service use.

7. In view of the insignificant penetration of ceramic coatings into the metal shell, it is believed that the metal properties are not affected appreciably. However, the firing temperature of the ceramic and the heat treatment of the metal must be carefully correlated to avoid damage to either the ceramic or the metal.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 14, 1953

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TABLE I. - COMPOSITION OF ACID-NICKEL SOLUTIONS USED FOR NICKEL COATING TURBINE BLADES[a]

	Solution	
	I	II
Nickel chloride, $NiCl_2 \cdot 6H_2O$, g/liter	30	--
Nickel sulfate, $NiSO_4 \cdot 7H_2O$, g/liter	--	30
Sodium hypophosphite, $NaH_2PO_2 \cdot H_2O$, g/liter	10	10
Sodium hydroxyacetate, $NaC_2H_3O_3$, g/liter	10	--
Sodium acetate, $NaC_2H_3O_2 \cdot 3H_2O$, g/liter	--	10
pH	4 to 6	4 to 6
Rate of deposition, in./hr	0.0005	0.001

[a]Information from table 3 of reference 11.

TABLE II - SUMMARY OF FABRICATION AND OPERATING DETAILS

Blade	Type of coating	Blade material	Blade profile (fig. 1)	Heat treatment (table III)	Time of test conditions		Coolant flow ratio	Condition of coating	Remarks
					[a]Cycles	Steady-state hr			
[b]1	Ceramic, modified NBS A-19	SAE 4130 cast	C	None	20	2.3	0.048	Extensive chipping on leading and trailing edges and suction surfaces	
[b]2	Ceramic, modified NBS A-19	SAE 4130	A	None		4.7	.048	Entire coating flowed toward tip; metal exposed at leading and trailing edges	
3	Ceramic, Solaramic 8042/3FE	Timken 17-22A(S)	A	5		11.2	.048	Excellent at 8 hr inspection	Blade failed at 1/3 span as result of loss of cooling-air supply
4	Ceramic, Ferro Corp. XT-955 (modified NBS A-19)	SAE 4130	A	1		15.9	.048	Excellent at last inspection (8.2 hr)	Twisted blade, failed in fatigue at root
5	Ceramic, Ferro Corp. XT-955 (modified NBS A-19)	SAE 4130	A	1		100.0	.048	Excellent throughout; original markings on coating still evident; no corrosion at leading edge where damaged by debris	Pressure surface bowing out and pulling loose from tubes at conclusion of test
6	Nickel	SAE 4130	A	1		44.1	.048	Coating chipped off leading edge and worn of trailing edge; good condition elsewhere	Pressure surface bowed out and pulled away from tubes
7	Nickel	Timken 17-22A(S)	A	6		8.0	.048	Good	Damaged by failure of another blade
[b]8	Nickel	Timken 17-22A(S)	A	6	107		.03	Coating eroded away on leading and trailing edges and corrosion set in; corrosion evident at leading edge after 76 cycles	Outer 1/3 of pressure surface failed because of corrosion, poor bond, and vibration
[b]9	Nickel	SAE 4130	A	2	59		.03	Coating wearing off leading and trailing edges	Blade failed at 1/3 span as result of loss of cooling-air supply
[b]10	Nickel	SAE 4130	A	None	2		.03		Blade elongated and rubbed against tail cone
[b]11	Nickel	SAE 4130	A	2	46		.03	Coating eroded away from leading and trailing edges	Blade still serviceable
[b]12	Nickel	SAE 4130	B	2		24.0 5.0 26.3	.048 .038 .030	Coating chipped off leading edge at 25 hr and a scale formed; blade was recoated; coating completely gone from leading edge and other local areas at completion of test	Blade was thermocoupled for temperature distribution tests after 55.2 hr
[b]13	Nickel	SAE 4130	B	2		5.0 1.0	.048 .030	Good	Pressure surface pulled away from tubes
[b]14	Uncoated for 21 hr, then nickel coated	SAE 4130	B	2		21.0 5.0 25.3	.048 .038 .030	Uncoated blade corroded badly in 21 hr; subsequent coating blistered in 10 hr; at 51.2 hr coating had scaled off in some areas; leading edge was bare and had corroded badly	Portion of blade broken away from pressure surface at tip
15	Nickel	Timken 17-22A(S)	B	7		23.9	.03	Coating chipped off leading edge near tip; excellent condition elsewhere	Damaged by failure of a standard blade

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16	Nickel with Nicrobraz on leading edge	Timken 17-22A(S)	B	7		100.0 1.2	.048 .03	Leading edge good where Nicrobrazed; scaling on rear third of suction surface on trailing edge and near root on leading edge	Damaged by failure of blade 21
17	Nickel with Nicrobraz on leading edge	Timken 17-22A(S)	B	7		11.4	.048	Good	Fatigue failure at blade root
18	Nickel with Nicrobraz on leading edge	Timken 17-22A(S)	B	7		23.7	.048	Good except for nickel scaling off leading edge near root	Fatigue failure at blade root
19	Nickel with Nicrobraz on leading edge	Timken 17-22A(S)	B	7		24.1 1.5	.048 .03	Leading edge very good; slight flaking at midchord near tip on both surfaces	Damaged by failure of blade 22
20	Nickel with Nicrobraz on leading edge	Timken 17-22A(S)	B	7		100.0	.048	Very good; slight flaking where leading edge was hit and on trailing edge	Tests concluded upon reaching 100 hr
21	Nicrobraz	Timken 17-22A(S)	B	7		100.0 1.2	.048 .03	Excellent at all stages of operation	Fatigue failure at blade root
22	Nicrobraz	Timken 17-22A(S)	B	7		30.0 1.5	.048 .03	Excellent	Fatigue failure at blade root
23	Nicrobraz	Timken 17-22A(S)	B	7		5.9	.048	Excellent	Fatigue failure at blade root
24	Aluminized (pack process)	SAE 4130	A	1		100.0	.048	Very good except where hit by debris	Tests concluded upon reaching 100 hr
25	Aluminized (pack process)	SAE 4130	A	1		8.0	.048	Very good	Shell pulled out of base
26	Aluminized (dip process)	Timken 17-22A(S)	B	4		124.4	.03	Excellent except for damage near root resulting from application of fillet	Tip damaged by standard blade failure at 5.7 hr; blade cut back to 3.92 in.
27	Aluminized (dip process)	Timken 17-22A(S)	B	4		124.4	.03	Excellent except for damage near root resulting from application of fillet and for tip damage	Tip damaged by standard blade failure at 24 hr; blade cut back to 3.35 in.
28	Aluminized (dip process)	Timken 17-22A(S)	B	4		118.7	.03	Excellent except for damage near root resulting from application of fillet	Tip damaged by standard blade failure at 17.2 hr; blade cut back to 2.65 in.; cracks at base after 118.7 hr
29	Aluminized (dip process)	Timken 17-22A(S)	B	4		100.6	.03	Excellent except where hit by debris and where ground away at tip	Blade stretched and rubbed against tail cone after 1 hr; cut back to 3.2 in.

[a]Cycle consisted of 15 minutes at rated test conditions followed by 5 minutes at idling conditions.
[b]Previously reported in reference 9.

TABLE III. - HEAT TREATMENTS APPLIED TO AIR-COOLED TURBINE BLADES

[All normalizing was done in an inert atmosphere.]

Heat-treatment number	Heat-treatment procedure
	SAE 4130 steel blades
1	Normalize at 1600° F for 30 minutes; air cool to room temperature. Draw at 1000° F for 15 minutes; air cool to room temperature.
2	Heat in 1800° F salt bath for 15 minutes followed by isothermal quench in 1000° F salt bath; hold for 15 minutes. Air cool to room temperature.
3	Heat in 2000° F salt bath for 15 minutes followed by isothermal quench in 1000° F salt bath; hold for 15 minutes. Air cool to room temperature.
	Timken 17-22A(S) steel blades
4	Normalize at 1725° F for 30 minutes; air cool to room temperature. Draw at 1225° F for 6 hours; air cool to room temperature.
5	Normalize at 1750° F for 30 minutes, cool to room temperature in nitrogen blast. Draw at 1225° F for 4 hours; cool in nitrogen blast.
6	Heat in 1800° F salt bath for 15 minutes followed by isothermal quench in 1200° F salt bath; hold for 15 minutes. Air cool to room temperature.
7	Normalize at 2075° F for 15 minutes followed by cooling in hydrogen atmosphere at rate equivalent to air cool. Draw at 1225° F for 4 hours followed by air cool to room temperature.

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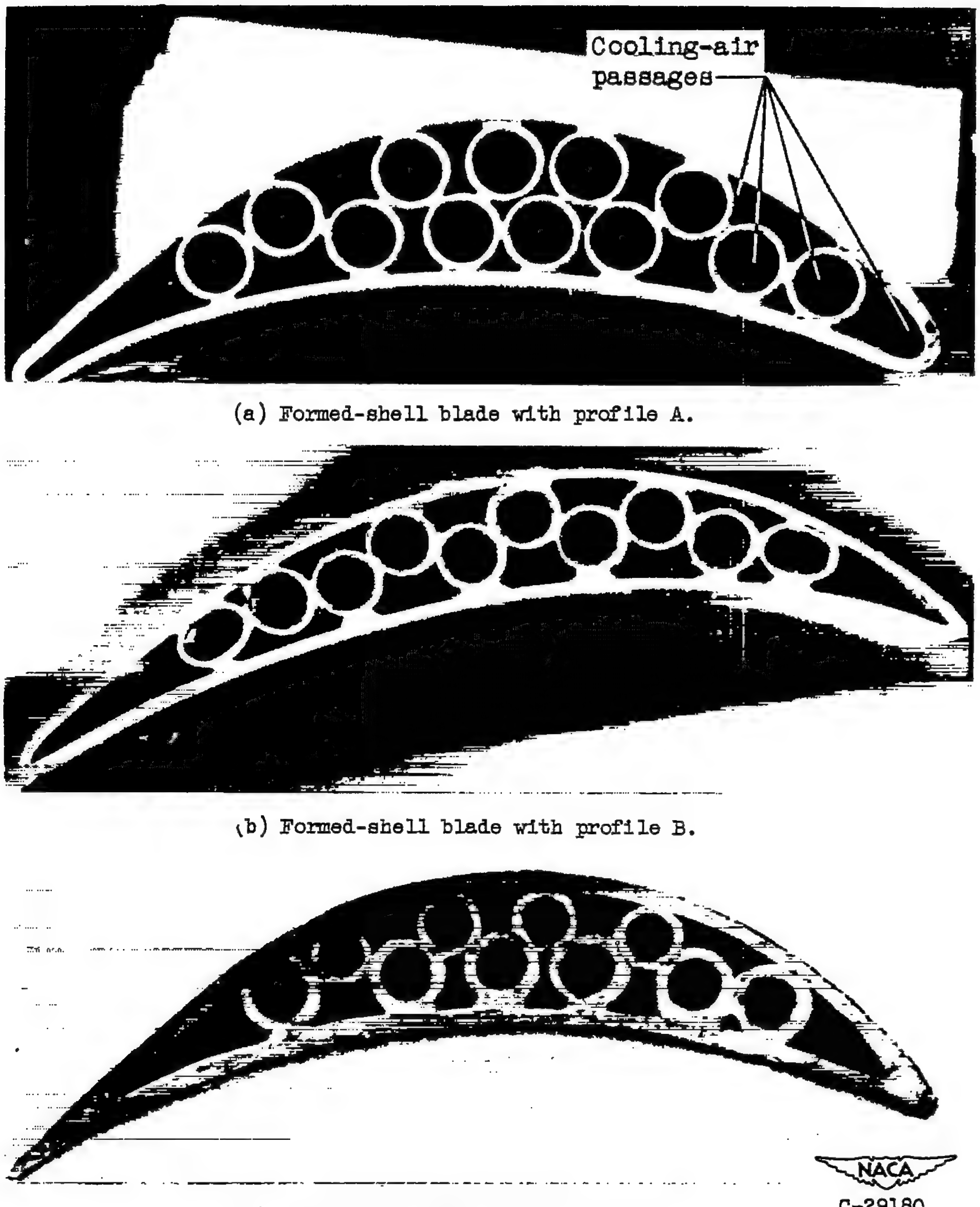
CX-4 back

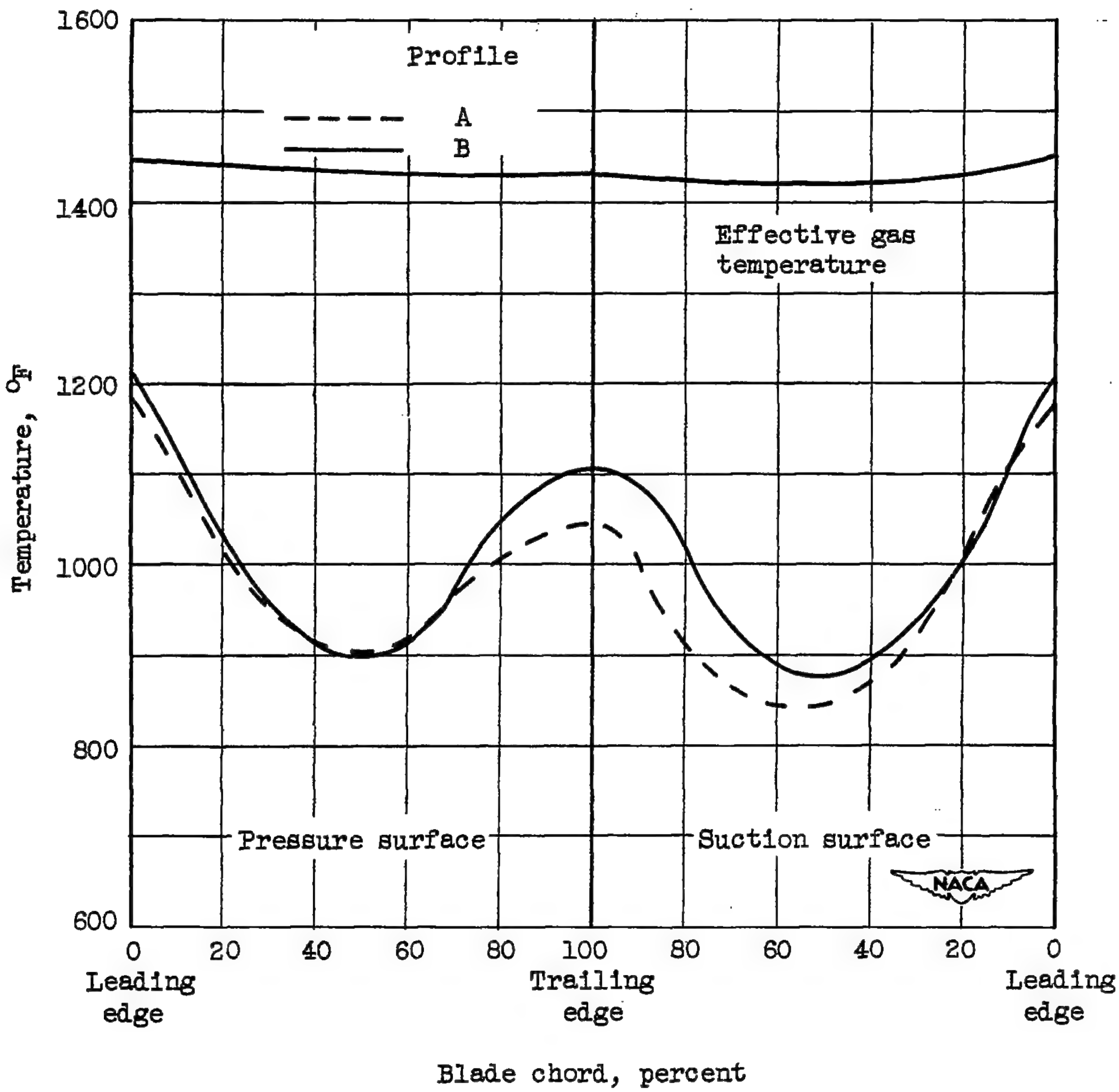


(a) Formed-shell blade with profile A.

(b) Formed-shell blade with profile B.

(c) Cast-shell blade with profile C.

Figure 1. - Cross sections of experimental blades.



(a) Coolant-flow ratio, 0.03.

Figure 2. - Peripheral temperature distribution at section $2\frac{9}{16}$ inches from tip for blades of profiles A and B.

[redacted]

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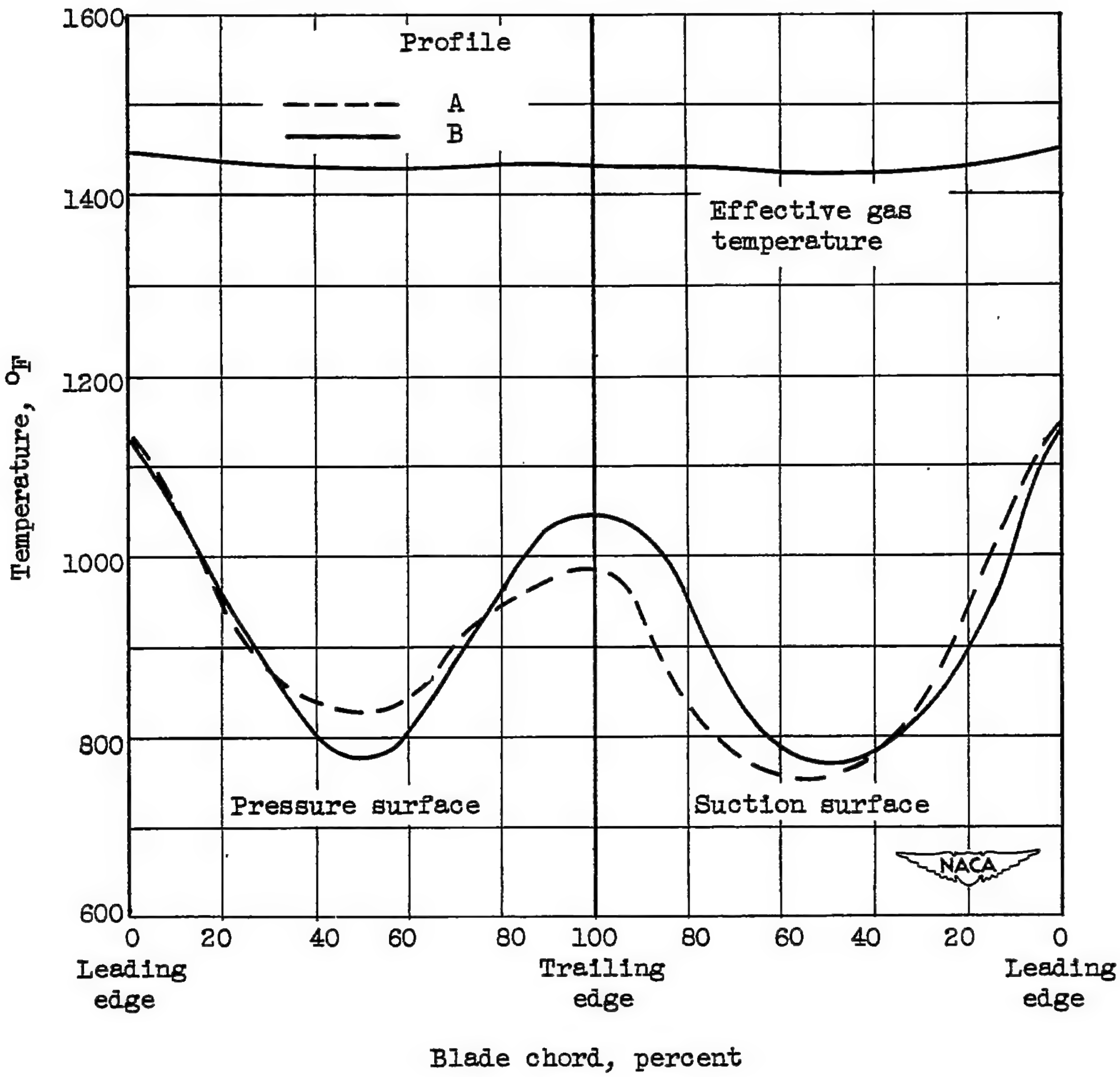
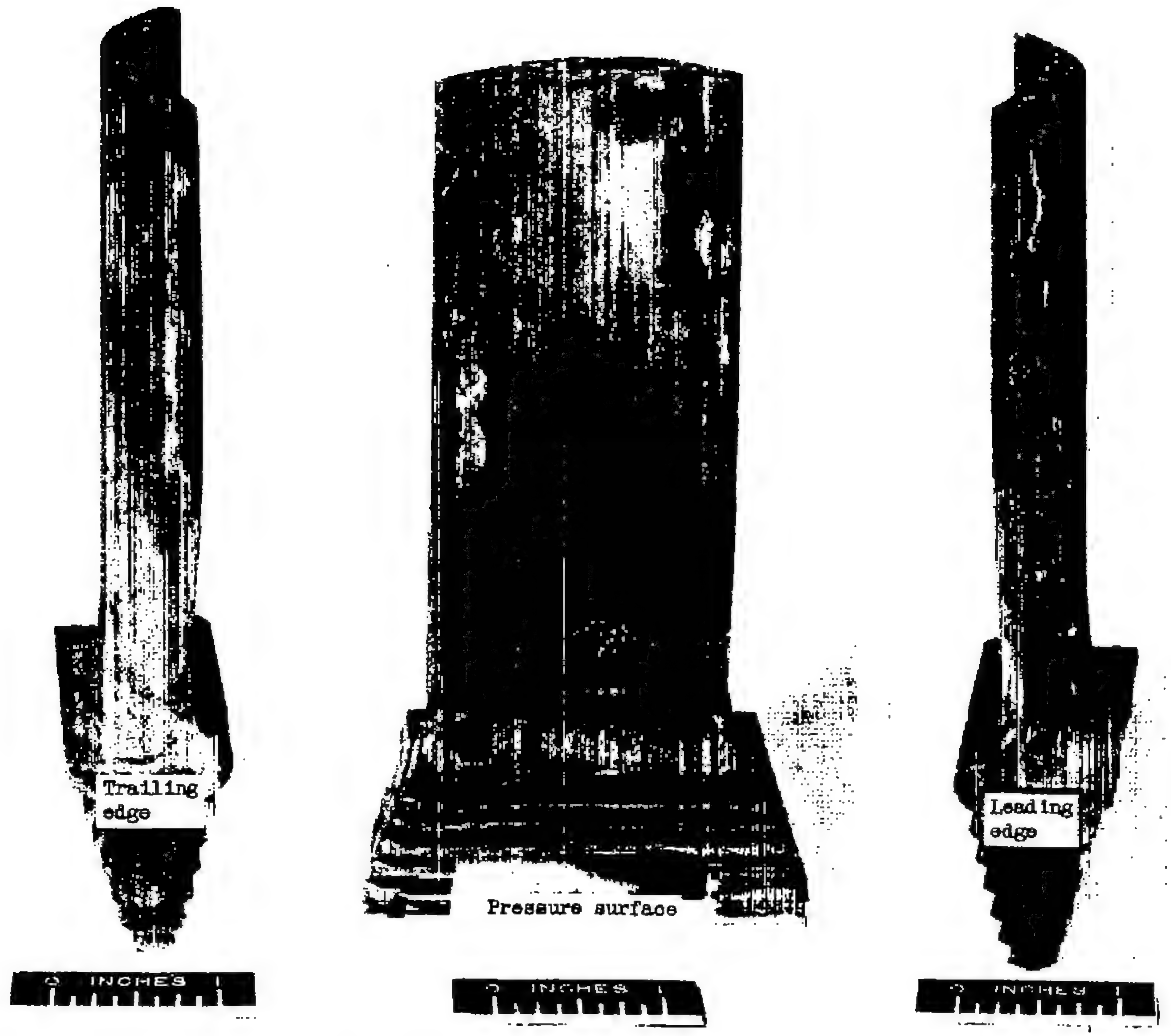


(b) Coolant-flow ratio, 0.05.

Figure 2. - Concluded. Peripheral temperature distribution at section $2\frac{9}{16}$ inches from tip for blades of profiles A and B.



C-28046

(a) Blade 1 after 7.3 hours (20 cycles plus 2.3 hours at rated test conditions) with coolant-flow ratio of 0.048. Complete breakdown of coating along leading and trailing edges evident.

Figure 3. - Typical ceramic-coating failures.

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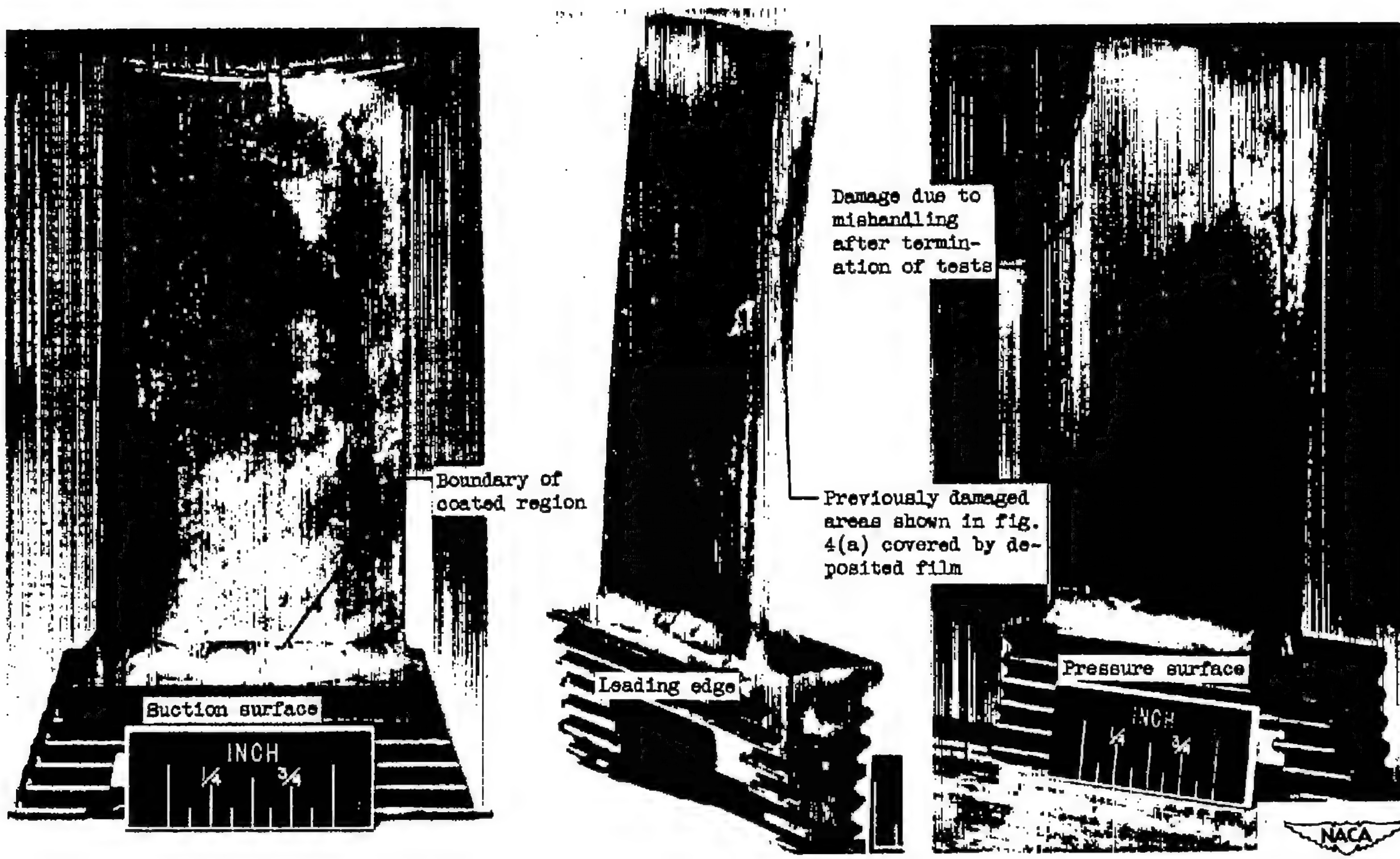
(b) Blade 2 after 4.8 hours at rated test conditions with coolant-flow ratio of 0.048. Coating softened and flowed toward tip.

Figure 3. - Concluded. Typical ceramic-coating failures.

[redacted]

(a) Blade 5 after 34.3 hours at rated test conditions with coolant-flow ratio of 0.048. Coating in excellent condition except where damaged by foreign objects striking blade.

Figure 4. - Ceramic-coated blade 5.



C-32340

(b) Blade 5 after 100 hours at rated test conditions with coolant-flow ratio of 0.048. Coating in excellent condition except where hit by foreign objects.

Figure 4. - Concluded. Ceramic-coated blade 5.

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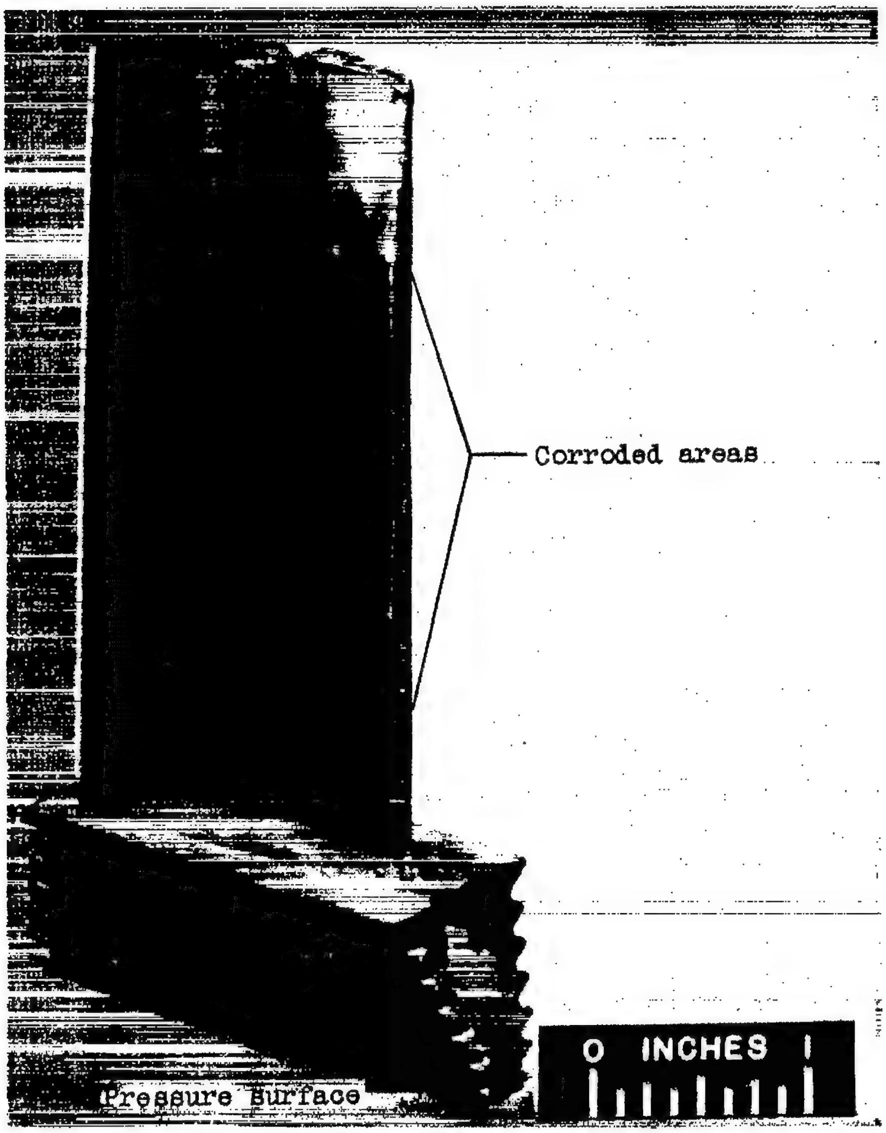

NACA
C-32341

(a) Blade 12 after 55.3 hours at rated test conditions with coolant-flow ratio of 0.03 to 0.048. Coating completely eroded away at leading edge and blistered and flaked in scattered areas over entire blade.

Figure 5. - Typical nickel-coating failures.

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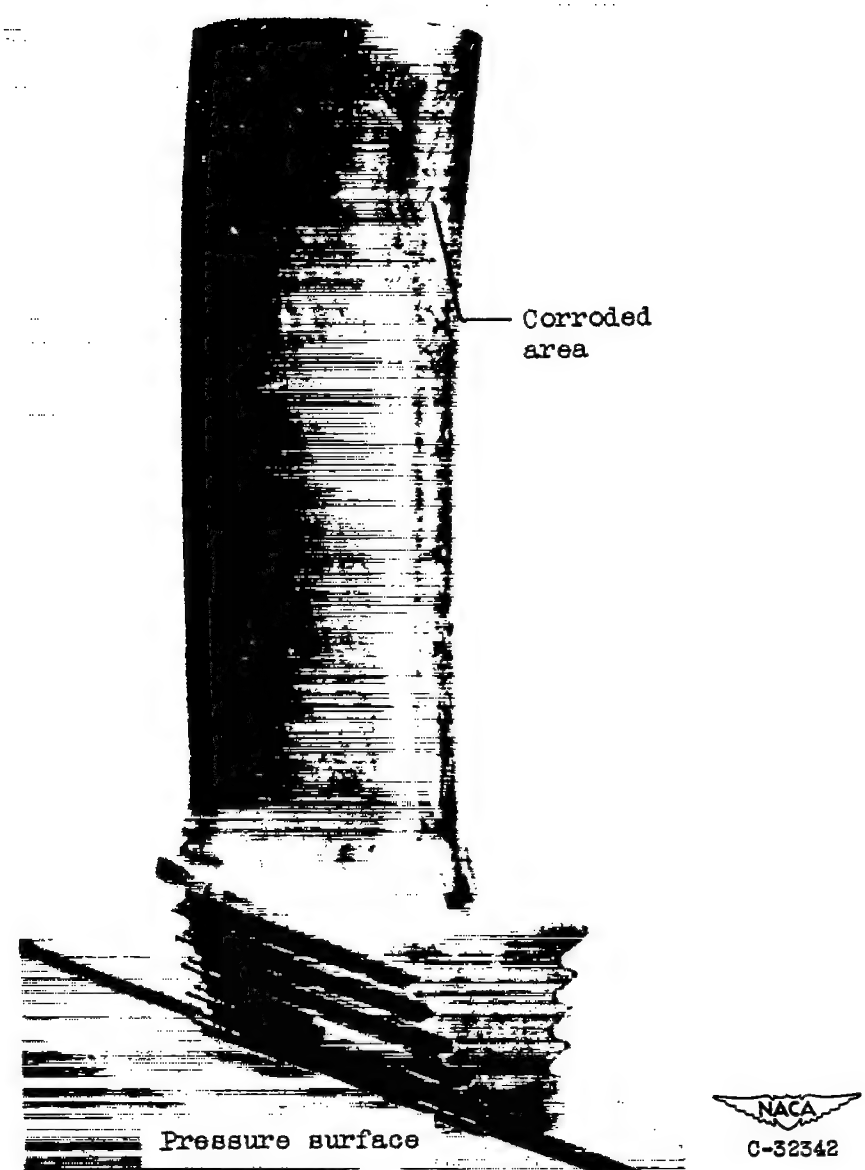
CX-5 back



(b) Blade 6 after 44 hours at rated test conditions with coolant-flow ratio of 0.048. Coating chipped and eroded on leading edge and eroded along trailing edge. Leading edge corroded near tip.

Figure 5. - Concluded. Typical nickel-coating failures.

[redacted]

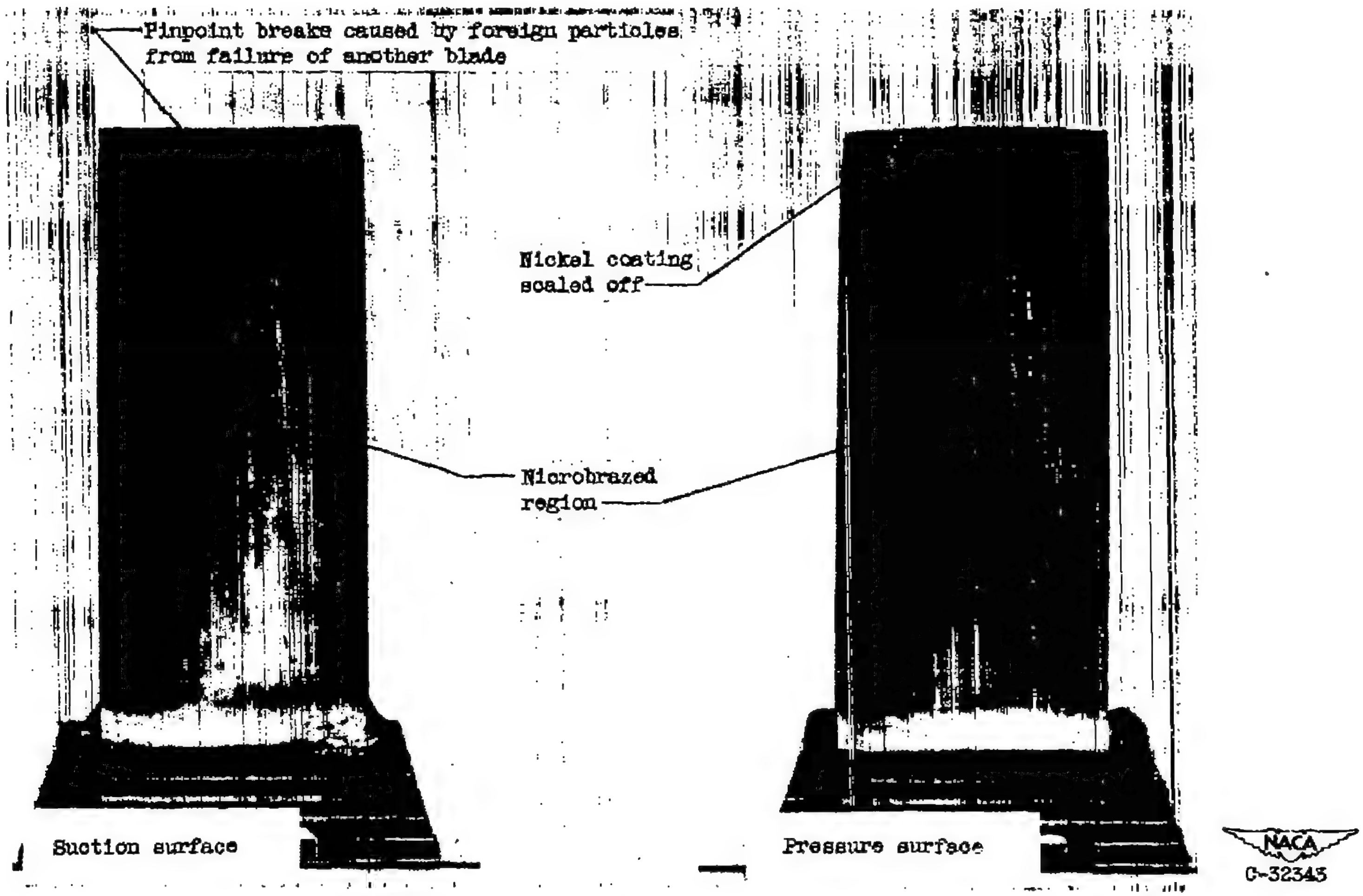
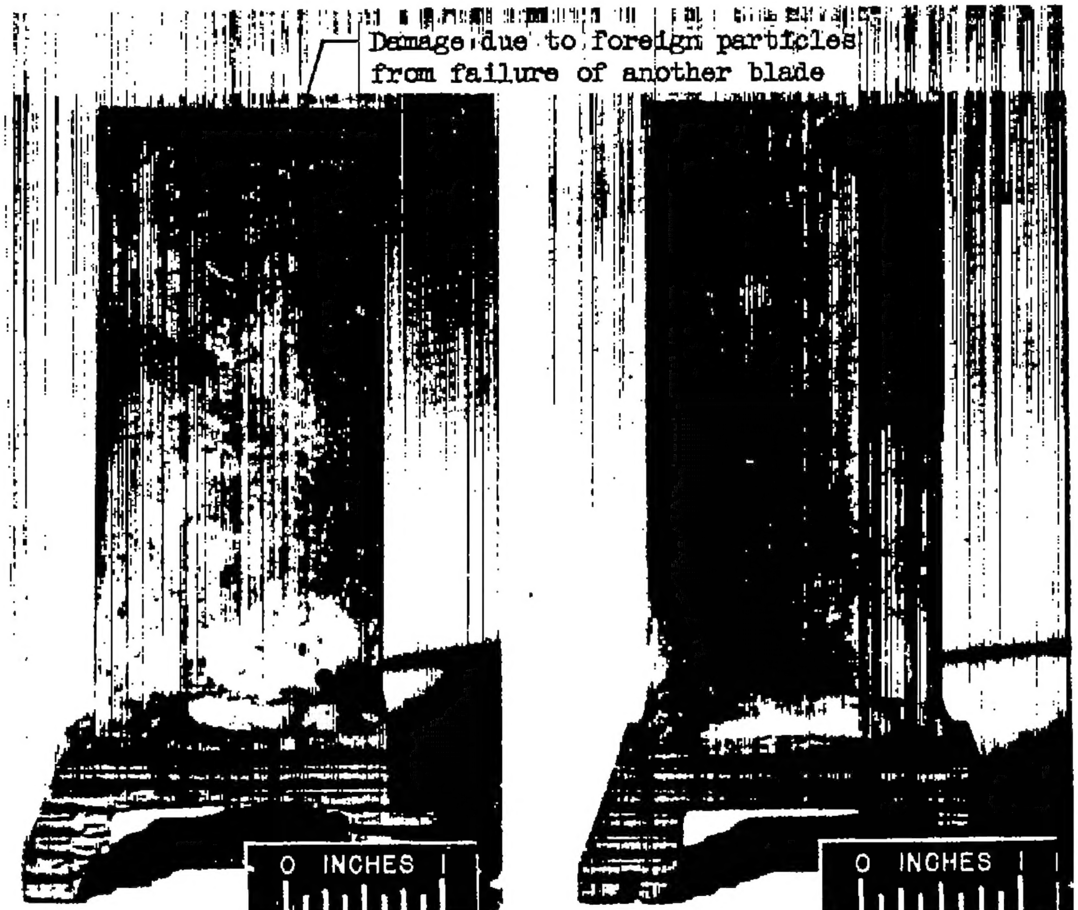


Figure 6. - Nickel-coated blade 20 with Nicrobraz along leading edge. Blade after 100 hours at rated test conditions with coolant-flow ratio of 0.048. Leading edge and midchord region in excellent condition.



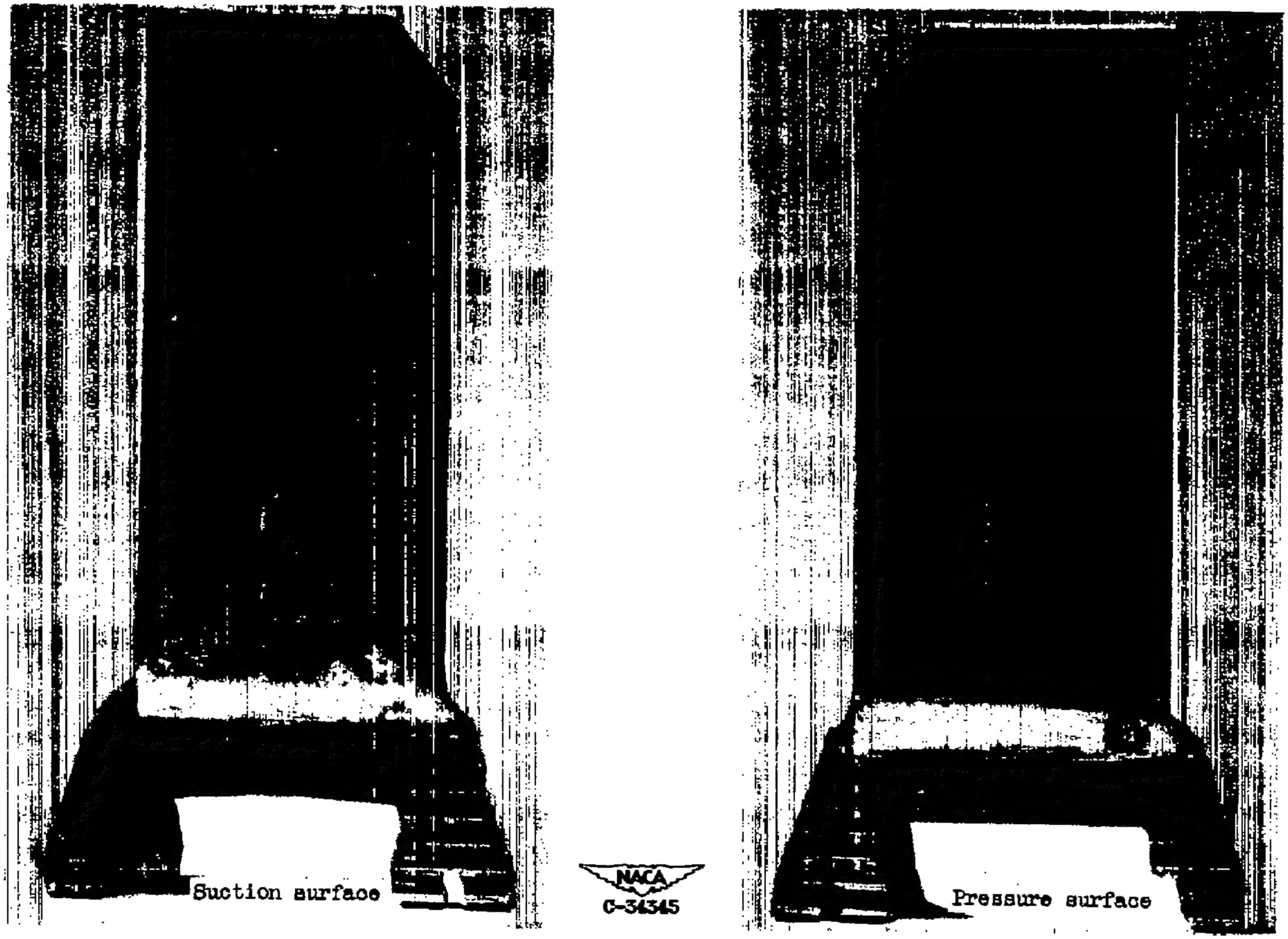
Suction surface

Pressure surface

C-32344

(a) Blade after 50 hours at rated test conditions with coolant-flow ratio of 0.048. Blade surfaces in excellent condition except where hit by foreign particles.

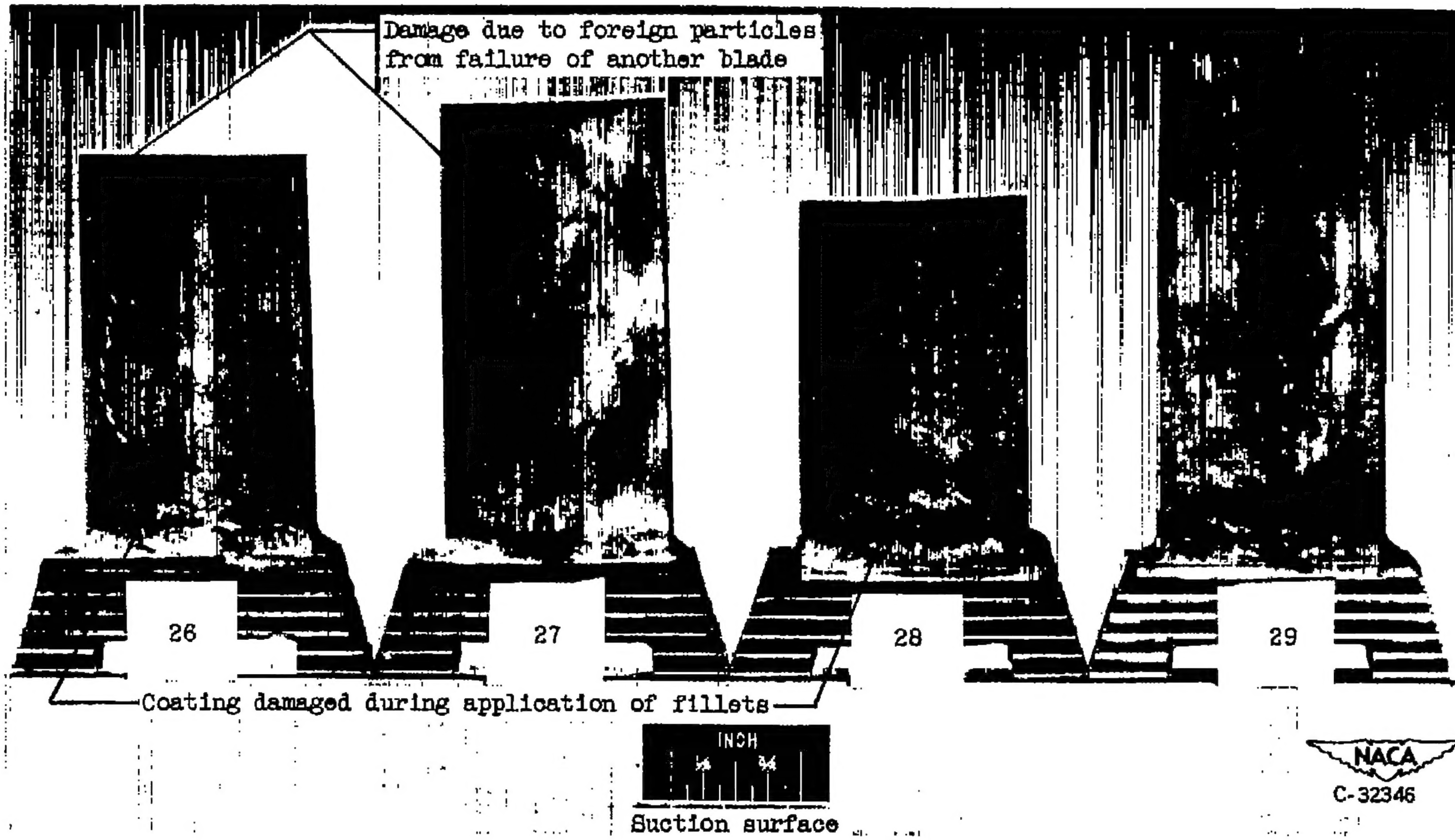
Figure 7. - Aluminized blade 24.



(b) Blade after 100 hours at rated test conditions with coolant-flow ratio of 0.048. Surfaces in excellent condition. Previously damaged areas shown on figure 7(a) indistinguishable from adjoining surfaces.

Figure 7. - Concluded. Aluminized blade 24.

CONFIDENTIAL



(a) Blades during early stages of endurance running with coolant-flow ratio of 0.03. Time on blades 26 and 27, 23.8 hours; on blade 28, 18.1 hours; on blade 29, no time. Surfaces in excellent condition.

Figure 8. - Aluminized blades 26, 27, 28, and 29.

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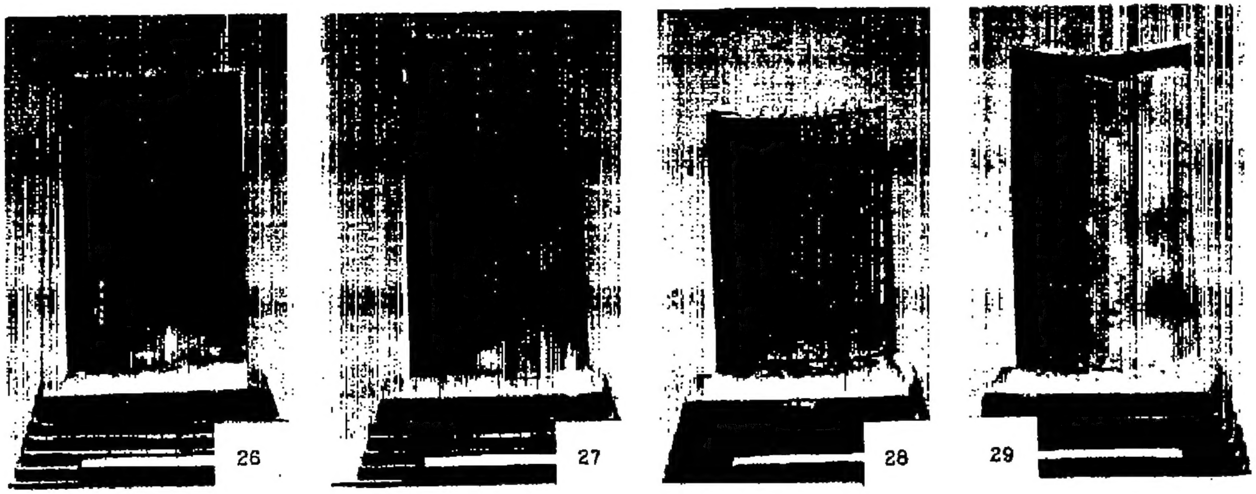
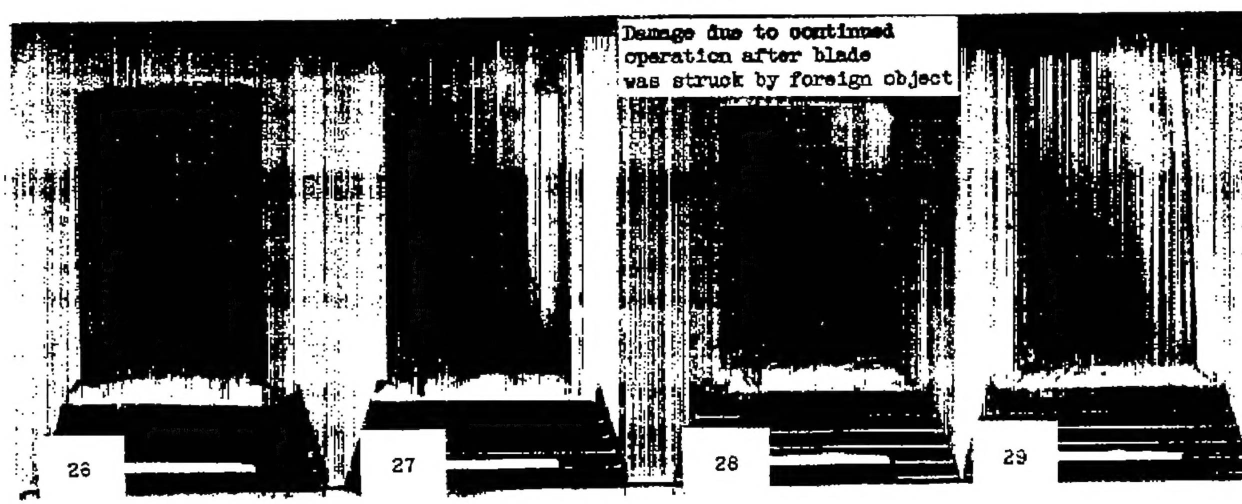


Suction surface



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Pressure surface

(b) Blades at conclusion of endurance running with a coolant-flow ratio of 0.03. Time on blades 26 and 27, 124.4 hours; on blade 28, 118.7 hours; on blade 29, 100.6 hours. Surfaces in excellent condition.

Figure 8. - Concluded. Aluminized blades 26, 27, 28, and 29.